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Original Article

Effect of Various Parameters on the Strength of Flyash and GGBS Geopolymer Mortar

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Abstract - *Geopolymers are a special class of inorganic polymers that are now promising binders developed by the activation of solid-state alumina-silicate with alkaline solution. Due to their environmental sustainability, geopolymers have been shown to be effective substitutes for cement binders in recent times. Additionally, its performance in an aggressive environment is encouraging, and these binders are gradually replacing cement concrete as a preferred option in aggressive situations. Numerous binders, including flyash, GGBS, metakaolin, and Palm Oil Flyash (POFA), have been the subject of extensive research, either alone or in combination with one or both binders. The current study's goal is to ascertain how different Liquid-to-Binder ratios (LB Ratio), NaOH molarities (M), and sodium silicate-to-sodium hydroxide ratios (alkaline solution ratio) affect the compressive strength of geopolymer mortar based on flyash and GGBS. The molarities of NaOH used in the study are 10 M, 12 M, 14 M, and 16 M. The investigations are carried out by altering the liquid binder ratio of 0.4 and 0.45. The ratios of sodium hydroxide to sodium silicate are 1.5, 2.0, and 2.5. A total of twenty-four experimental mixes of flyash and GGBS are made for each geopolymer mortar. The qualities of the fresh mortar are ascertained, together with the compressive strengths. The effect of various molar ratios on the compressive strength of flyash and GGBS mortar is studied. From the above studies, the geopolymer mortar with GGBS has shown improved results compared to the geopolymer mortar with flyash. Among all the mixes the mix with 14M exhibited superior performance in compressive strength. The specimens with an LB ratio of 0.45, AL ratio of 2.0 and 14M yielded a maximum strength of 52.69 MPa.*

Keywords - *Molarity, Flyash, GGBS, Setting time, Sodium hydroxide molarity.*

1. Introduction

Geopolymers are inorganic polymer materials that share a lot of chemical similarities with zeolites, which are hydrated aluminosilicates of calcium, magnesium, sodium, and potassium. Alkali activation of aluminosilicate materials, comprising base materials like flyash, granulated blast furnace slag, etc., and activators like sodium silicate, sodium hydroxide, and potassium hydroxide, results in the formation of geopolymers. It is composed of base materials containing silicon and aluminum that are activated by mixing alkaline solutions that act as a binder. Alkali-activated flyash mortars underwent a four-stage hardening mechanism. Initially, flyash particle surfaces were negatively ionized by alkali activators. Second, the silica–alumina glassy chain of flyash particles was easier to dissolve when OH was present. Third, condensation-crystallization produced reaction products. Reaction products eventually accumulate [1]. The creation of gel phases (C-S-H and A-S-H) and the compaction of the microstructure with the addition of slag are responsible for the improvement in the structure and characteristics of the flyash-based geopolymer [2]. The specimen's strength improved with the addition of NaOH and Na_2SiO_3. After aging for seven days, the optimum geopolymer mortar mixture's strength was 40 MPa, suggesting that flyash-based geopolymer might replace portland cement in the concrete industry [3]. A review of the literature on the strength properties of geopolymer indicated the addition of GGBFS significantly improved the strength of the geopolymer mortar. This may be explained by the quick hydraulic reactivity and granular structure of GGBFS, which quickens the calcium reaction and causes Calcium Silicate Hydrate (C-S-H) and Aluminosilicate Hydrate (C-A-S-H) gels formation [4]. The compressive strength increases when GGBS is partially substituted for flyash. It is possible to achieve strengths of 80 MPa with just M+ (alkali dosage) 7.5% and Alkali Modulus (AM) 1.25. Another advantage of these mixes is that they don't require high drying temperatures; room temperature curing is sufficient [5]. A slump value of 90 mm or more is considered to be achieved for a highly workable geopolymer. Owing to the considerable vibration caused by compaction, slump values between 50 and 89 mm are categorized as medium workability, while those below 50 mm are regarded as low workability [6].

Previous studies on the effect of sodium hydroxide molarity and alkaline solution ratio have been carried out utilizing flyash and GGBS as a full replacement or partial replacement with varying parameters. Therefore, the reported study investigated the influence of various parameters on the fresh properties and compressive strength of flyash and GGBS mortar independently while maintaining uniform molarity, alkaline solution ratio, and liquid binder ratios for both flyash and GGBS-based geopolymer mortars. A comparative study of flow, setting time, and strength properties of flyash and GGBS mortar were carried out. The different parameters include the liquid binder ratios of 0.4 and 0.45, the sodium hydroxide to sodium silicate ratios of 1.5, 2.0, and 2.5, and the molarities of NaOH of 10M, 12M, 14M, and 16M.

2. Experimental Program

2.1. Materials

In this study, the flyash used has a specific gravity of 2.24, and the finess is 362 m^2/kg. The specific gravity of GGBS is 2.76, and the fineness is 410 m^2/kg. The chemical composition of flyash and GGBS are provided in Table 1.

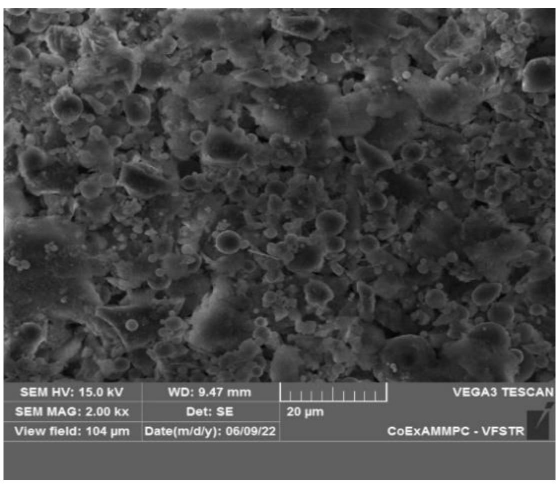

Fig. 1(a) SEM images of flyash sample

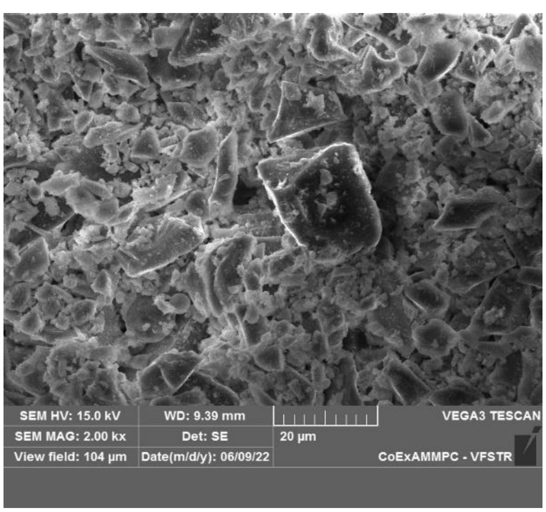

Fig. 1(b) SEM images of GGBS sample

Manufactured sand available from local sources is procured. The specific gravity of the sand is 2.67, which confirms Zone II as per IS 383. Analytical grade sodium hydroxide (NH) with 97% purity in the form of pellets was dissolved in water to prepare the solution of various concentrations for the study.

Sodium silicate was procured from the local supplier. The properties of alkaline solution (NH & NS) are listed in Tables 2 and 3, respectively. The flyash consists mainly of primary particles that are spherical in shape, whereas GGBS particles are more angular, as seen in Figures 1(a) and 1(b).

Table 1. Composition of flyash and GGBS

Composition (% by Weight)	Flyash	GGBS
SiO_2	49.13	28.82
Fe_2O_3	-	-
Al_2O_3	34.21	16.44
CaO	5.22	48.82
MgO	3.07	5.49
SO_3	-	-
Na_2O	3.17	-
K_2O	5.2	0.44
LOI	0.27	2.20

Table 2. Composition of NaOH

Chemical Composition	Percentage
Sodium Hydroxide	97
Carbonate	2
Chloride	0.01
Sulphate	0.01
Phosphate	0.001
Iron	0.005
Lead	0.001

Table 3. Composition of sodium silicate

Chemical Composition	Percentage
Na_2O	14.3
SiO_2	29.8
Ratio of $Na_2O:SiO_2$	1:2.08
Total Solid %	44.1
Water Content	55.9

Table 4. Mix proportions of Geopolymer mortar with flyash/GGBS

Mix ID Flyash/GGBS	L/B Ratio	AL Ratio	NaOH Concentration (M)	Sand (kg/m^3)	Flyash (kg/m^3)	Na_2SiO_3 (kg/m^3)	NaOH (kg/m^3)	Water (kg/m^3)
F/G0.4-1.5-10	0.40	1.5	10	1431.82	477.00	50.50	23.90	116.00
F/G0.4-1.5-12			12				27.50	112.80
F/G0.4-1.5-14			14				30.80	109.50
F/G0.4-1.5-16			16				33.90	106.40
F/G0.4-2.0-10		2.0	10			56.10	19.90	114.80
F/G0.4-2.0-12			12				22.90	111.80
F/G0.4-2.0-14			14				25.70	109.00
F/G0.4-2.0-16			16				28.20	106.50
F/G0.4-2.5-10		2.5	10			60.10	17.10	113.60
F/G0.4-2.5-12			12				19.70	111.00
F/G0.4-2.5-14			14				22.00	108.70
F/G0.4-2.5-16			16				24.20	106.50
F/G0.45-1.5-10	0.45	1.5	10	1415.70	472.00	56.10	26.60	129.50
F/G0.45-1.5-12			12				30.60	125.50
F/G0.45-1.5-14			14				34.30	121.80
F/G0.45-1.5-16			16				37.70	118.40
F/G0.45-2.0-10		2.0	10			62.40	22.20	127.70
F/G0.45-2.0-12			12				25.50	124.30
F/G0.45-2.0-14			14				28.60	121.30
F/G0.45-2.0-16			16				31.40	118.40
F/G0.45-2.5-10		2.5	10			66.90	19.00	126.40
F/G0.45-2.5-12			12				21.90	123.50
F/G0.45-2.5-14			14				24.50	120.90
F/G0.45-2.5-16			16				26.90	118.50

2.2. Mix Design and Specimen Preparation

The Trial mixes for geopolymer mortar are carried out with parameters such as LB Ratio – 0.40 and 0.45, alkaline solution Ratio – 1.5, 2.0 and 2.5 and molarity of sodium hydroxide solution – 10,12,14 and 16. In order to attain uniformity in the design and comparison of outcomes, as well as to determine the ideal mix proportions, the parameters for flyash and GGBS were maintained constant. A total of 48 experimental mixes have been completed, 24 of which included flyash and 24 with GGBS. Table 4 lists the proportions of the geopolymer mortar containing GGBS and flyash. The nomenclature used to identify the blends between the flyash and GGBS is "F" stands for flyash, "0.4" for liquid binder ratio, "1.5" for alkaline solution ratio, and "10" for molarity of NaOH.

Similar to this, G0.4-1.5-10 denotes GGBS mix with a liquid binder ratio of 0.4, an alkaline solution ratio of 1.5 and a NaOH molarity of 10M. Alkali activators include sodium hydroxide (97 percent pure) in pellets form and sodium silicate solution. The alkali activator solution was created by diluting NaOH pellets with water. Before combining the solution with the sodium silicate solution, it was allowed to cool to ambient temperature for 24 hours. A pan mixer was used for the trial mixing of the geopolymer mortars. Five minutes prior, the alkali activator solution was added to the binder material; it was combined with water and superplasticer. After adding the alkali activator solution to the mixture and including the binder, the mixer was turned on for five minutes.

After adding the sand, the mixer is run for a total of three minutes, making a thirteen-minute mixing period. Cubes with dimensions of 70 mm were cast for compressive strength in the current study. In all, 288 specimens were cast for GGBS mortar and flyash mortar, respectively, in order to conduct a strength test.

2.3. Curing

All the specimens were demoulded twenty-four hours after casting. The cube specimens were stored at room temperature for curing until the day of testing.

3. Testing

The tests to determine the 28-day strength compressive strength were carried out using a 2000 KN capacity compression testing machine. The average compressive strength of 3 cubes was determined.

4. Results and Discussion

4.1. Workability

The workability of geopolymer concrete is generally lower than that of regular portland concrete. The sticky characteristic that silicate imparts may be the cause of the reduced workability of geopolymer concrete. However, geopolymer mortar, even with a low slump value, can be compacted well on a vibrating table. The degree of compaction determines the workability of the geopolymer. A slump of 90 mm or more is considered to be achieved for a highly workable geopolymer. Owing to the considerable vibration caused by compaction, slump values between 50 and 89 mm are categorized as medium workability, while those below 50 mm are regarded as low workability [6]. A flow table was used to measure the geopolymer mortar's flow in accordance with the ASTM C 1437. Two layers of mortar were poured into the mold, leveled the top surface, and tamped 20 times for each layer. The flow table is raised, lowered, and rotated 25 times in a 15-second period as the mold is gradually raised. Three directions were used to measure the mortar spread's diameter, and the average of those measurements was noted. Figures 2, 3, and 4 compare the flow of geopolymer mortar with flyash and GGBS for liquid binder ratios of 0.4 and 0.45 for various molarities.

4.1.1. Effect of NaOH Molarity on the Flow of Mortar

From Figures 2, 3 and 4, it is observed that when the molarity of the NaOH solution increases, the flow is decreasing. The liquid binder ratios of 0.40 and 0.45 exhibit the same tendency.

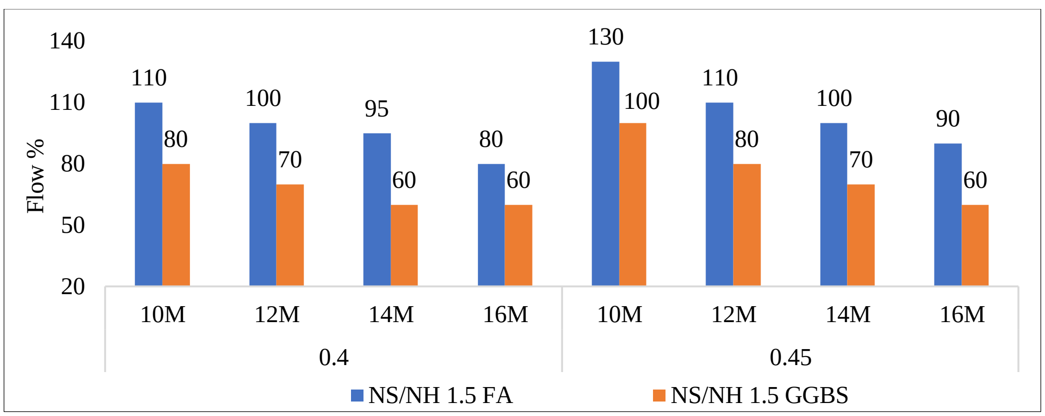

Fig. 2 Workability (%) of flyash and GGBS geopolymer mortar for different molarity and liquid binder ratios. Alkaline solution ratio 1.5

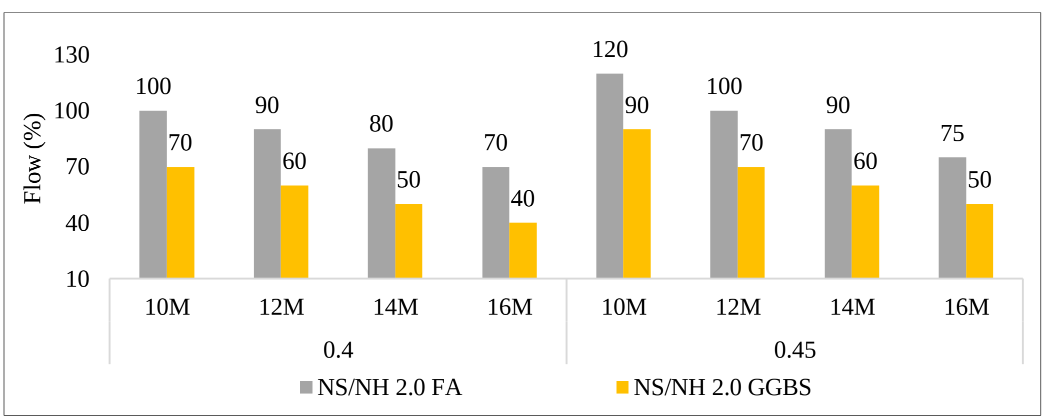

Fig. 3 Workability (%) of flyash and GGBS geopolymer mortar for different molarity and liquid binder ratios. Alkaline solution ratio 2.0

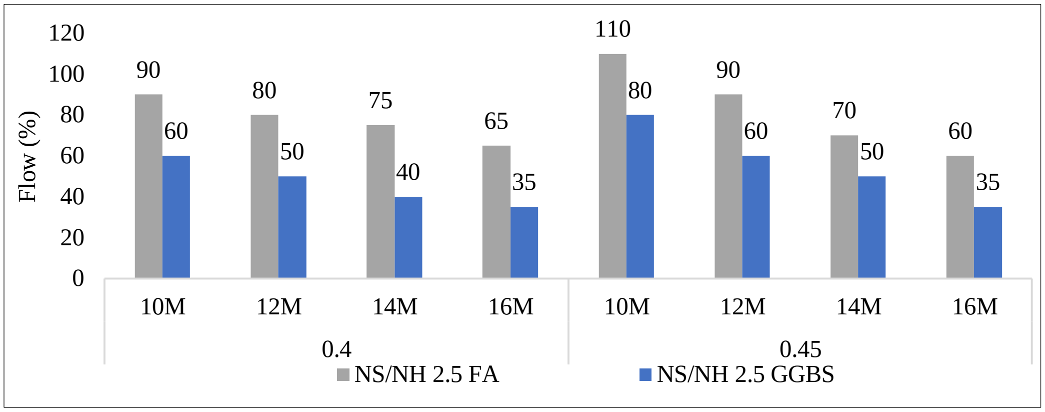

Fig. 4 Workability (%) of flyash and GGBS geopolymer mortar for different molarity and liquid binder ratios. Alkaline solution ratio 2.5

By comparing the flow of GGBS and flyash geopolymer mortar, Figure 2. It was discovered that flyash mortar is more workable than GGBS mortar. In flyash and GGBS mortars, the flow reduced as the molarity of NaOH increased. Flyash mortar flow (%) varies between 110 and 80 for molarities of 10M and 16M, respectively. Similarly, for molarities of 10M and 16M, respectively, the flow (%) for GGBS mortar is 80 to 60. The flow (%) of flyash mortar with a liquid binder ratio of 0.45 is 130 to 90 for molarities of 10M and 16M, respectively. The flow (%) for GGBS mortar is 100 to 60. When compared to the 16M molarity, the 10M molarity slump value was higher. The slump value of flyash mortar with 16M dropped by 37.5% when compared to the slump with 10M at a liquid binder ratio of 0.40. When the GGBS mortar with 16M was compared to a 10M slump, the slump value of the former dropped by 33.33%. The slump values of GGBS mortar and flyash mortar fell by 66% and 44%, respectively, for 16M at a liquid binder ratio of 0.45 as compared to the mix of 10M. The primary source of the flow reduction is the sodium hydroxide solution's increased viscosity with increasing molarity. For the combinations containing GGBS, the effect of molarity was more noticeable. For molarities of 10M and 16M, respectively, the flow values of GGBS mortar demonstrate reductions of 37.5% and 33.33% as compared to flyash mortar. Similar to this, when compared to the same flow of flyash mortar, the flow values of GGBS mortar decreased by 30% and 50% for molarities of 10M and 16M at a liquid binder ratio of 0.45.

Figure 3 illustrates how the flow values of GGBS mortar for molarities of 10M and 16M, respectively, are reduced by 42.86% and 75% when compared to flyash mortar. Similarly, as compared to equivalent flyash mortar, the flow values of GGBS mortar decreased by 33.33% and 50% for molarities of 10M and 16M at a liquid binder ratio of 0.45. From Figure 4, it is observed that, for molarities of 10M and 16M, respectively, the flow values of GGBS mortar are reduced by 50% and 85% when compared to flyash mortar. Similarly, as compared to equivalent flyash mortar, the flow values of GGBS mortar decreased by 37.50% and 71.43% for molarities of 10M and 16M at a liquid binder ratio of 0.45. The flow of flyash-based geopolymer mortar is affected by the concentration of NaOH in terms of molarity and solutions-to-flyash ratios [7].

4.1.2. Effect of Alkaline Solution Ratio on Flow of Mortar

The flow of flyash for alkaline solution ratios of 1.5, 2.0 and 3.0 with varying molarities are shown in Figures 5 and 6. The flow of GGBS mortar for alkaline solution ratios with varying molarities is shown in Figures 7 and 8.

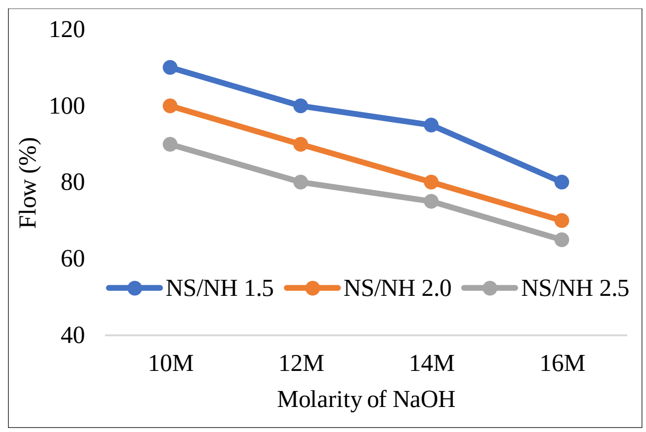

Fig. 5 Workability (%) of flyash geopolymer mortar for various alkaline solution ratios and liquid binder ratio of 0.4

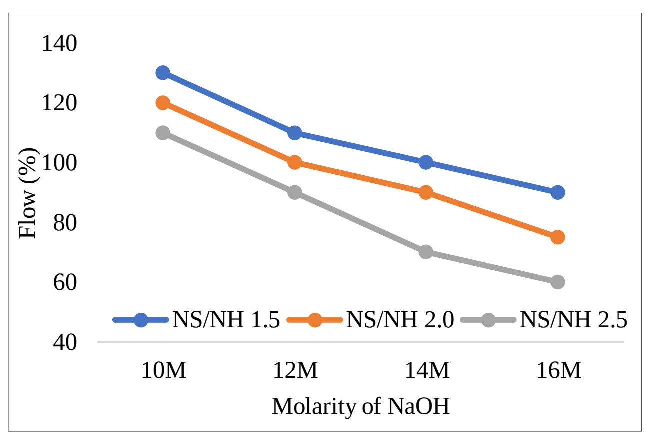

Fig. 6 Workability (%) of flyash geopolymer mortar for various alkaline solution ratios and liquid binder ratio of 0.45

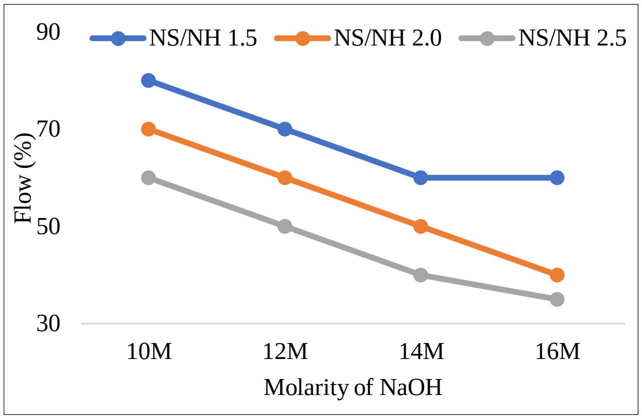

Fig. 7 Workability (%) of GGBS geopolymer mortar for various alkaline solution ratios and liquid binder ratio of 0.4

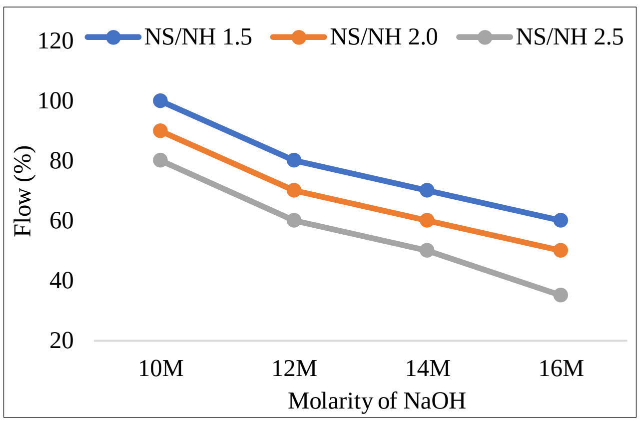

Fig. 8 Workability (%) of GGBS geopolymer mortar for various alkaline solution ratios and liquid binder ratio of 0.45

It is evident from Figures 5 to 8 that the flow values of flyash mortar and GGBS mortar are higher for the alkaline solution ratio (NS/NH), which is 1.5. The flow value decreases with higher NS/NH ratios. Since sodium silicate is mostly viscous, a rise in the alkaline solution ratio increases viscosity, which reduces workability. The percentage reduction in the flow of flyash and GGBS mortar for varying alkaline solution ratios are given in Tables 5 and 6.

Table 5. Workability of Flyash & GGBS geopolymer mortar for varying Alkaline solution ratio, liquid binder ratio of 0.40

L/B Ratio	Increase/Decrease in Flow				
	Molarity	Flyash		GGBS	
		NS/NH 1.5 - 2.0	NS/NH 1.5-2.5	NS/NH 1.5 -2.0	NS/NH 1.5-2.5
0.40	10	10.00	22.22	14.29	33.33
	12	11.11	25.00	16.67	40.00
	14	18.75	26.67	20.00	50.00
	16	14.29	23.08	50.00	71.43

Table 6. Workability of Flyash & GGBS geopolymer mortar for varying Alkaline solution ratio, liquid binder ratio of 0.45

L/B Ratio	Increase/decrease in flow				
	Molarity	Flyash		GGBS	
		NS/NH 1.5 - 2.0	NS/NH 1.5-2.5	NS/NH 1.5 -2.0	NS/NH 1.5-2.5
0.45	10	8.33	18.18	11.11	25.00
	12	10.00	22.22	14.29	33.33
	14	11.11	42.86	16.67	40.00
	16	20.00	50.00	20.00	71.43

From Table 5, for molarities of 10M and 16M, respectively, the flow of flyash geopolymer mortar with NS/NH - 2.0 decreased by 10% and 14% in comparison with NS/NH - 1.5. Similarly, for molarities of 10M and 16M, respectively, the flow of flyash mortar with NS/NH – 2.5 demonstrated a reduction of 22% and 23% in comparison with NS/NH – 1.5. When GGBS mortar is used, the flow is reduced more significantly. For molarities of 10M and 16M, the highest reductions were 33% and 71% with NS/NH-2.5 and NS/NH-1.5, respectively.

Table 6 illustrates that for molarities of 10M and 16M, respectively, the highest reduction in the flow of flyash geopolymer mortar with NS/NH – 2.5 indicated a reduction of 18% and 50% in comparison with NS/NH –1.5. For molarities of 10M and 16M, the GGBS mortar demonstrated a maximum reduction of 25% and 71% with NS/NH-2.5 compared with NS/NH-1.5. The flow of the geopolymer mortar containing flyash and GGBS is influenced by the alkaline solution ratio.

From the above results, it is seen that the flow values of the GGBS geopolymer mortar decreased in comparison with flyash GPM. This could be attributed to two main factors which are responsible for the improved slump retention in flyash: first, the smooth, spherical shape of the flyash particles, which improves the mobility of the constituent materials in the mix; and second, flyash does not readily undergo geopolymerization at room temperature, resulting in an extended setting time for the mixture.

Further, regardless of the activating solution's content, the flow value of flyash geopolymer mortar was higher than that of slag-based geopolymer. The spherical flyash particles promote the mortar's free flow, but the slag particles being angular impede the flow because of their increased interlocking. Moreover, the alkali solution becomes more viscous due to the slag's alumino-silicates dissolving more quickly. The flow decreases with the increase in alkali solution content. As the NaOH solution's viscosity rises, the mortar stiffens, and its flow decreases. The lubricating effect of the alkaline solution accounts for a greater flow at lower NaOH concentrations. However, a highly concentrated alkaline solution reduces the flow diameter by making the pore fluid more cohesive, which restricts the flow. The current study's findings with flyash mortar and GGBS mortar are consistent with the earlier studies [8, 9].

4.2. Setting Time

Vicat apparatus is used to determine the Initial Setting Time (IST) and Final Setting Time (FST) of the geopolymer mortar mixtures in accordance with ASTM C191. The IST is considered accomplished when the needle penetrates the paste by no more than 25 mm. The FST is the length of time that passes after the plunger can no longer pierce the mortar's surface by a specific quantity.

4.2.1. Effect of NaOH Molarity on Setting Time

The setting time of geopolymer mortar with flyash and GGBS for various molarities is shown in Figures 9-11. Figure 9 illustrates how the setting times reduce as the molarity of the sodium hydroxide solution increases. The initial setting time of flyash geopolymer mortar for molarities of 10M and 16M ranges from 130mm to 50mm for a liquid binder ratio of 0.4. For molarities of 10M and 16M, the appropriate final setting time values range from 190mm to 140mm. Similar to this, for molarities of 10M and 16M, respectively, the initial setting time for GGBS mortar is between 100 and 40 mm, and the final setting time is between 150 and 100 mm.

Furthermore, the initial setting time of flyash geopolymer mortar for molarities of 10M and 16M, respectively, ranges from 155 mm to 70 mm for a liquid binder ratio of 0.45. For molarities of 10M and 16M, the corresponding final setting time values range from 250 mm to 150 mm. Similar to this, for molarities of 10M and 16M, respectively, the initial setting time for GGBS mortar is between 120 and 60 mm, and the final setting time is between 170 and 150 mm.

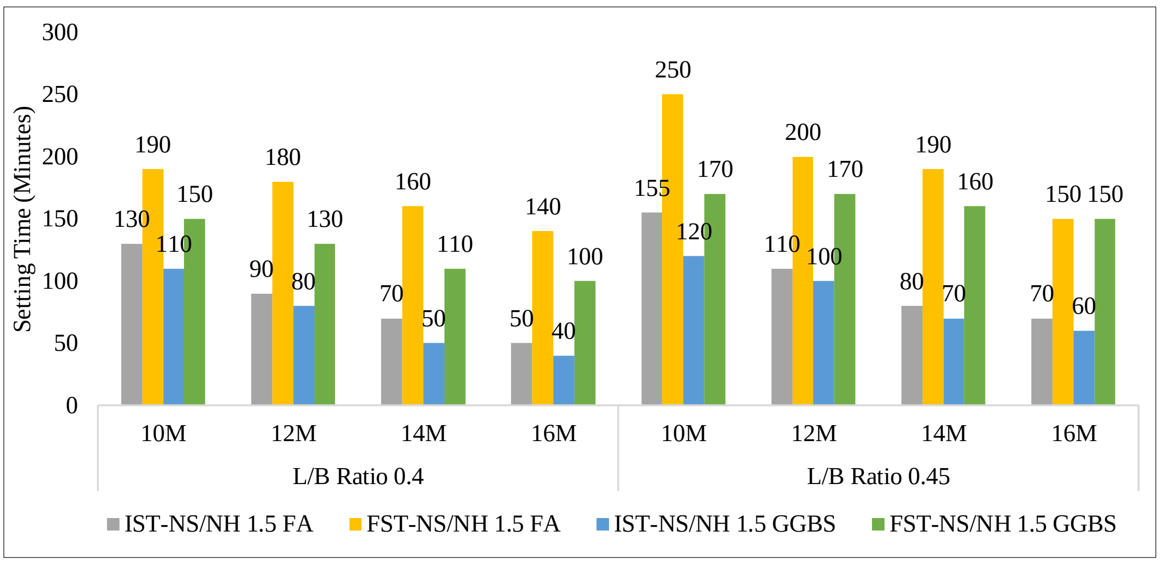

Fig. 9 Setting time of flyash and GGBS geopolymer mortar for different Molarity and liquid binder ratios. Alkaline solution ratio 1.5

Flyash geopolymer mortar's initial setting time for molarities of 10M and 16M ranges from 120mm to 50mm for a liquid binder ratio of 0.4, as shown in Figure 10. For molarities of 10M and 16M, the appropriate final setting time values range from 180mm to 130mm. Similarly, for molarities of 10M and 16M, respectively, the final setting time for GGBS mortar is 140mm to 80mm, and the initial setting time is between 90mm and 50mm. Furthermore, the setting time of flyash geopolymer mortar for molarities of 10M and 16M, respectively, ranges from 140 mm to 60 mm for a liquid binder ratio of 0.45. For molarities of 10M and 16M, the corresponding final setting time values range from 200 mm to 140 mm. Similarly, for GGBS mortar, for molarities of 10M and 16M, respectively, the ultimate setting time is 150mm to 110 mm, and the initial setting time is between 100mm and 60mm.

Flyash geopolymer mortar's initial setting time for molarities of 10M and 16M ranges from 110mm to 40mm for a liquid binder ratio of 0.4, as shown in Figure 11. For molarities of 10M and 16M, the appropriate final setting time values range from 150mm to 100mm. Similar to this, for GGBS mortar, molarities of 10M and 16M, respectively, require an initial setting time of 80mm to 40mm and a final setting time of 100mm to 70mm. Additionally, the flyash geopolymer mortar's initial setting time ranges from 130 mm to 60 mm for molarities of 10M and 16M, respectively, for a liquid binder ratio of 0.45. For molarities of 10M and 16M, the corresponding final setting time values range from 170 mm to 120 mm. Similarly, for GGBS mortar, for molarities of 10M and 16M, respectively, the ultimate setting time is 130mm to 70 mm, and the beginning setting time is between 100mm and 50mm.

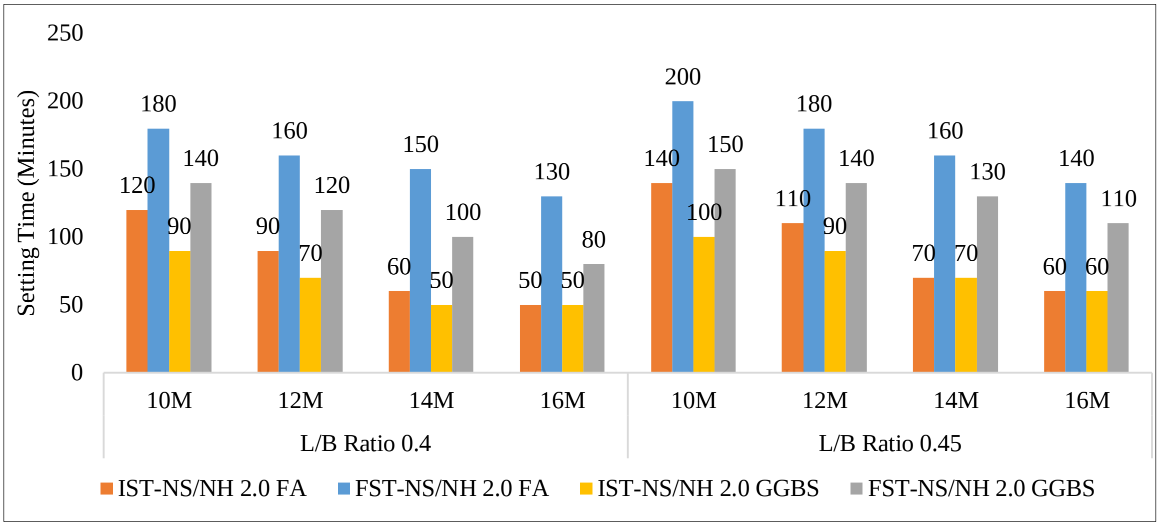

Fig. 10. Setting time of flyash and GGBS geopolymer mortar for different molarity and liquid binder ratios. Alkaline solution ratio 2.0

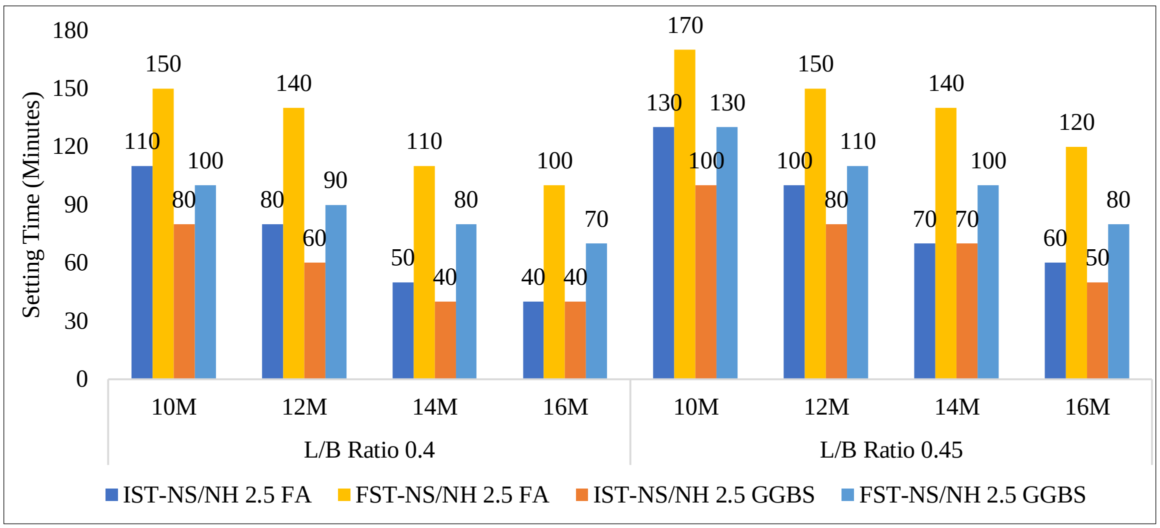

Fig. 11. Setting time of flyash and GGBS geopolymer mortar for different molarity and liquid binder ratios. Alkaline solution ratio 2.5

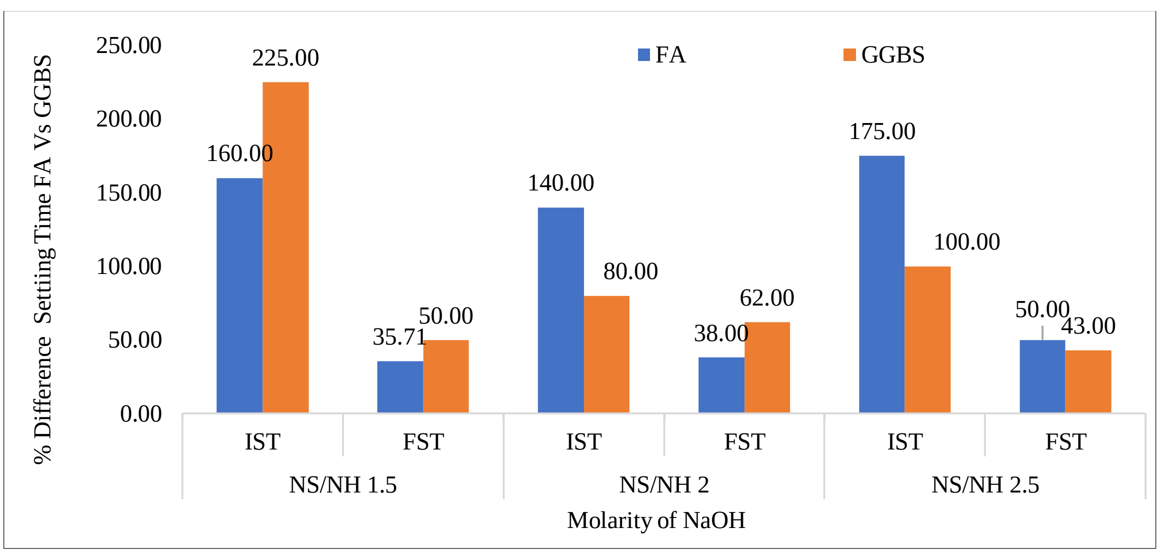

Fig. 12 Comparison of setting time of flyash and GGBS geopolymer mortar

From the results, it is seen that with an increase in the molarity of sodium hydroxide solution, the setting time has decreased. An increase in sodium hydroxide molarity would also have an impact on the alkaline liquid's silica modulus or the silicate molar ratio, which would have an impact on the alkaline activation process. With the increase in the liquid binder ratio, the setting time increases. The current study's findings demonstrated a similar pattern of setting times decreasing as sodium hydroxide molarity increased [10].

4.2.2. Effect of Alkaline Solution Ratio on Setting Time

The setting time of flyash mortar and GGBS mortar for different alkaline solution ratios of 1.5, 2.0 and 2.5 is shown in Figure 12.

From Figure 12, it is observed that the initial setting time of flyash was reduced by 160% for the specimen of 16M in comparison with the 10M and the final setting time was reduced by 35%. For GGBS, the reduction is significant when the molarity is increased. The initial setting time and final setting time decreased by 225% and 50%, respectively, for 16M in comparison with 10M. The alkaline ratio of the solution is 1.5. For an alkaline solution ratio of 2.0, the initial setting time of flyash was reduced by 140% for a specimen of 16M in comparison with the 10M and the final setting time was reduced by 38%. For GGBS, the reduction is significant when the molarity is increased. The initial setting time and final setting time decreased by 80% and 62.5%, respectively, for 16M in comparison with 10M. For an alkaline solution ratio of 2.5, the initial setting time of flyash was reduced by 175% for a specimen of 16M in comparison with the 10M and the final setting time was reduced by 50%. For GGBS, the reduction is significant when the molarity is increased. The initial setting time and final setting time decreased by 100% and 43%, respectively, for 16 M in comparison with 10M.

4.2.3. Comparision of Setting Time of Geopolymer Mortar with Flyash and GGBS

The Final Setting Time (FST) of flyash mortar and GGBS mortar are shown in Figures 13 to 15.

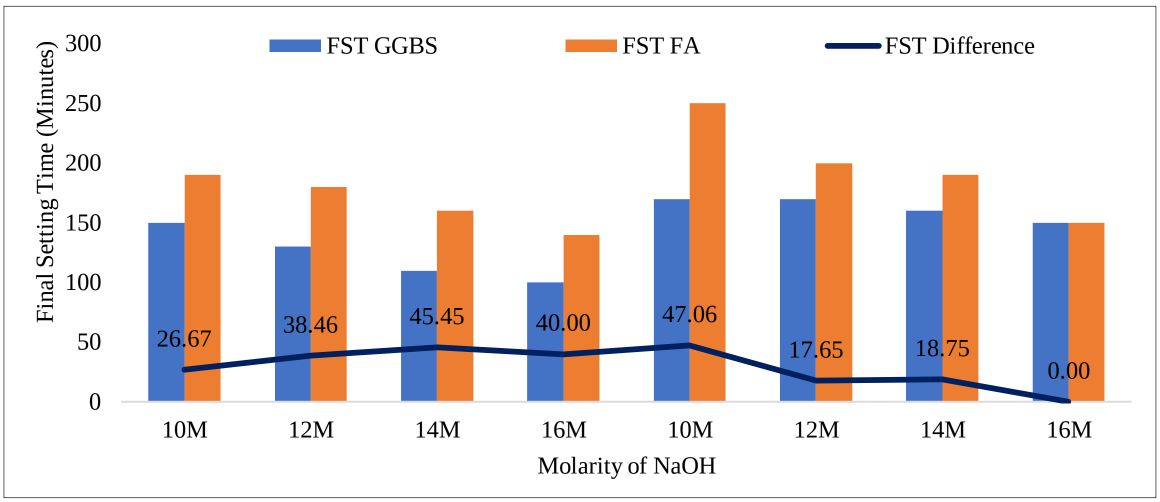

Fig. 13 Comparision of FST of flyash and GGBS geopolymer mortar alkaline solution ratio 1.5

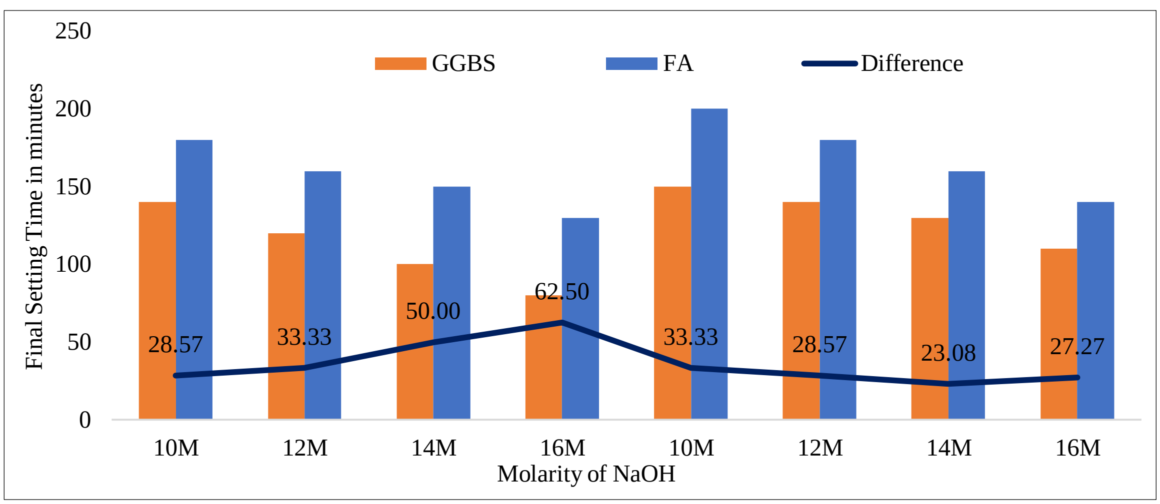

Fig. 14 Comparision of FST of flyash and GGBS geopolymer mortar alkaline solution ratio 2.0

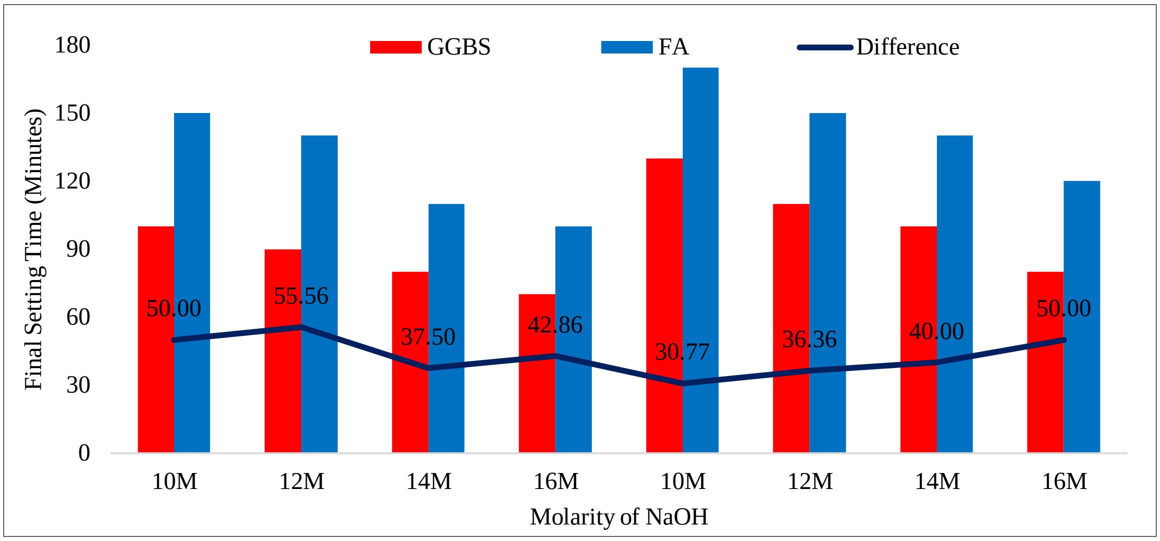

Fig. 15 Comparision of FST of flyash and GGBS geopolymer mortar alkaline solution ratio 2.5

Figures 13 to 15 demonstrate how the setting time of GGBS mortar is shorter than that of flyash mortar. The reduction is 26.67% to 40% for molarities of 10M and 16M, respectively, with an alkaline solution ratio of 1.5. The setting time decrease ranges from 28% to 62% for an alkaline solution ratio of 2.0. When compared to flyash mortar, the GGBS mortar showed a lower setting time at an alkaline ratio of 2.5. The range is between 50% and 42%, or 10M and 16M molarities of sodium hydroxide solution, respectively.

From the above study, it is seen that the GGBS mortar showed a shorter setting time than the flyash mortar. Compared to flyash, this tendency clearly shows that slag reacts more quickly with NaOH solution at room temperature. In an aqueous solution of NaOH, the release of Ca_{2+} ions occurs concurrently with the release of Si_{4+} and Al_{3+} ions from the slag particles. The pozzolanic reaction is supported by high calcium content in addition to the geopolymerization reaction. The geopolymeric reaction products and these additional hydration products shorten the setting times [9]. The rise in the SS/SH ratio from 1.5 to 2.5 increased the dissolute silica concentration. Consequently, the dissolute silica concentration may be the cause of the setting time decrease seen with an increase in the SS/SH ratio from 1.5 to 2.5. A greater concentration of dissolute silica would accelerate the alkali activation process and shorten the dissolving reaction's duration, which would shorten the setting time [10].

It has been noted that the setting time decreases as the alkaline activator concentration rises. Similar trends were noted for slag activated by solutions containing sodium hydroxide. The different effects of the SS/SH ratio on setting time may be attributed to the interaction between SS and SH. The primary cause can be ascribed to an increase in the relative quantity of SH, which raises the concentration of hydroxide ions in mixtures and speeds up raw material dissolving, hence reducing down the setting time. The results of the present study are in line with the previous works carried out [11-13].

4.3. Compressive Strength

The compressive strength values for mortar specimens are evaluated in this study. The result of the strength of flyash and GGBS geopolymer mortar with various sodium hydroxide molarities and liquid binder ratios of 0.40 and 0.45 are shown in Figures 16, 17 and 18.

Figure 16 shows that when the concentration of the sodium hydroxide solution increases, so does the strength of the GGBS and flyash mortars. For a liquid binder ratio of 0.4, GGBS mortar showed an increase of 100% strength in comparison with the flyash mortar for molarity of 14. Beyond 14M, the GGBS mortar's strength has reduced as its molarity has increased. With the liquid binder ratio increased to 0.45, GGBS mortar has demonstrated a 30% increase in compressive strength when compared to flyash mortar, with a liquid binder ratio of 0.45 and an alkaline solution ratio of 1.5.

Figure 17 shows that the strength of both flyash and GGBS mortar increases as the molarity of sodium hydroxide solution rises to 14M. However, as the molarity rises above 14M, the compressive strength of both flyash and GGBS mortar decreases with 16M molarity. At a liquid binder ratio of 0.4 and molarity of 14M, GGBS mortar showed an increase of 9% in compressive strength in comparison with flyash mortar. In comparison with flyash mortar for a liquid binder ratio of 0.45, GGBS mortar recorded an increase in compressive strength of 100% with an alkaline solution ratio of 2.0 and a molarity of 14. It has been noted that when molarity exceeds 14M, the strength of GGBS and flyash mortars decreases.

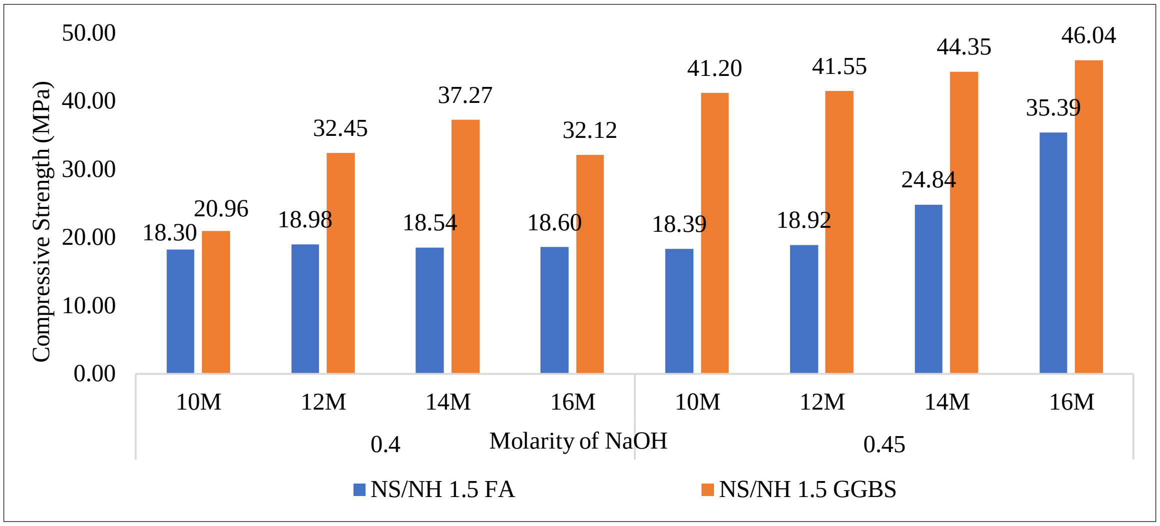

Fig. 16 Compressive strength of flyash and GGBS GPM mortar for Alkaline solution of 1.5

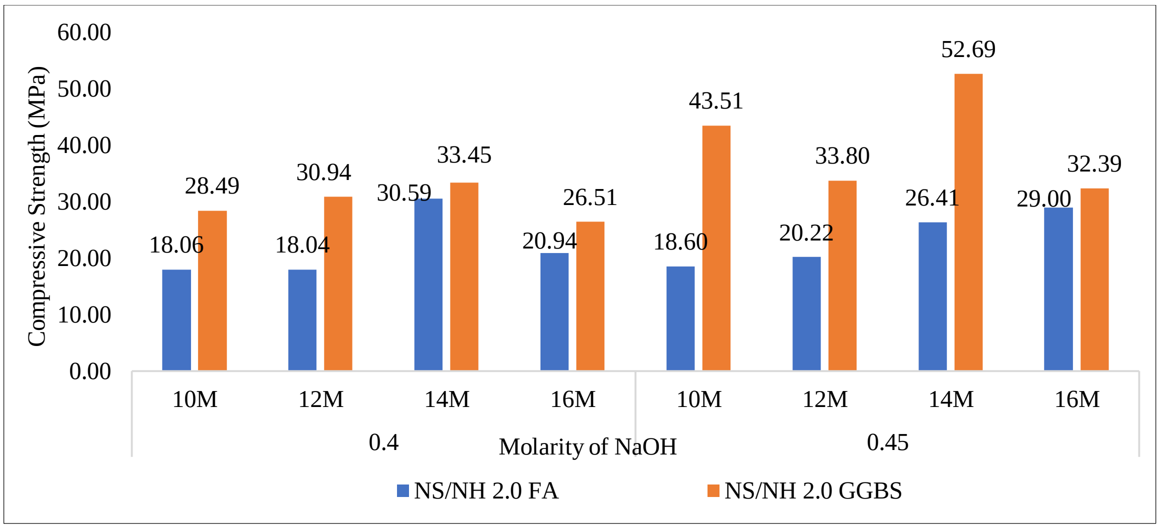

Fig. 17 Compressive strength of flyash and GGBS GPM mortar for Alkaline solution of 2.0

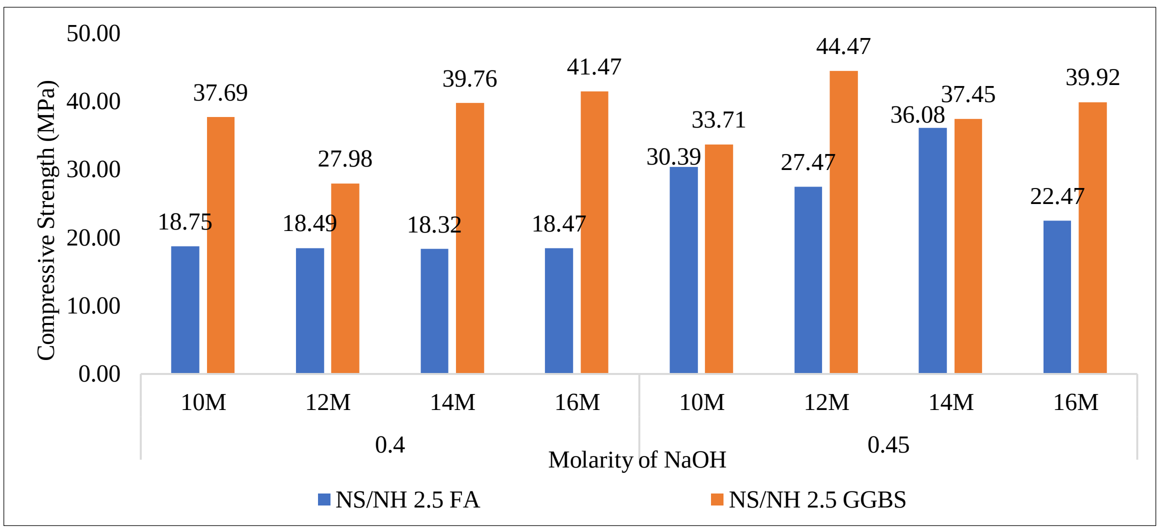

Fig. 18 Compressive STRENGTH OF FLYASH and GGBS GPM mortar for Alkaline solution of 2.5

From Figure 18 for a liquid binder ratio of 0.40 and molarity of 16M, GGBS mortar showed a 124% increase in compressive strength in comparison with the flyash mortar; GGBS mortar has demonstrated a 60% increase in compressive strength when compared to flyash mortar, with a liquid binder ratio of 0.45 and an alkaline solution ratio of 2.5 and molarity of 12.

A study on blended geopolymer paste and mortar made of flyash and slag showed that a maximum compressive strength of 31.0 MPa and a desirability value of 0.83 were obtained with 60% GGBS content and 8 M NaOH content [9]. The increase in GGBS concentration up to a 70% increase improves the compressive strength of geopolymer mortar. For strengths above 60 MPa, POFA up to 30% addition with GGBS is advised as it yielded the maximum strength. The compressive strength of geopolymer concrete increases with increasing GGBS (slag) concentrations [14]. The strength growth was facilitated by the GGBS particles, which were finer than flyash [15]. In a study carried out with concrete waste powder, in combination with GGBS, the strength increased in the ambient setting process. With a short period of curing, compressive strength can be achieved by using GGBS. This could be attributed to the GGBS particles, which are in smaller sizes, filling voids more effectively, which causes a reduction in porosity and water absorption in the process [16]. Flyash-based geopolymer with slag addition had compressive strengths of 53.1 MPa and 70.4 MPa, respectively, with curing temperatures of 300^0C and 700^0C at 14 days of testing [17]. By increasing the GGBS content up to 100% replacement flyash, the compressive strength reaches as high as 76MPa. The high calcium content present in GGBS results in the increase in concentration of alkaline activator, which plays a major role in compressive strength with different molarities of 8, 12, and 16M. It is observed that the strength in oven-cured specimens is greater than the ambient-cured specimens [18].

4.3.1. Effect of Molarity of Sodium Hydroxide Solution

The effects of sodium hydroxide on the flow and strength of a flyash-based geopolymer mortar were examined. Increased sodium hydroxide solution molarity at a particular curing temperature has been observed to improve the compressive strength of geopolymer mortar [7]. It was discovered that a higher concentration of NaOH solution had a more pronounced effect at all temperatures. Nevertheless, for 13.11 M and 15.08 M NaOH solutions, the compressive strength drops for solutions-to-flyash ratios of 0.45 and 0.50, respectively. The decrease at greater concentrations may be the result of incomplete compaction brought on by the fresh mix's increased viscosity and flowability [19]. The curing temperature and duration had an impact on the geopolymer mortar's physical properties. It was discovered that the amount of NaOH in the mortar had a substantial effect on its properties when it was cured at 85^0C. Compressive strength values of 21.3 MPa and 22 MPa, respectively, were obtained from the mortar with a 6 M concentration that was cured at 65^0C for 24 hours and a sample of the same mortar that was cured at 85^0C [9]. Strength is increased by the alkaline activator with greater molarity because it promotes the development of geo-polymeric gel and alumino silicates. Strength is increased by the activator solution's molarity, which indicates the concentration of salts in the solution [20]. The alkaline activator with higher molarity increased the formation of alumino silicates and geopolymeric gel, thereby increasing the strength. The molarity of the activator solution, which represents the concentration of the salts in the solution, results in an improvement in strength [21]. As the NaOH concentration and the mass ratio of w(Na2SiO3)/w(NaOH) increase, the compressive strength and Young's modulus of elasticity rise, peaking at a certain point before declining [22]. A study was conducted with sodium hydroxide molarity of 6 M, 8 M, 10 M, 12 M, 14 M, and 16 M NaOH and the ratio of flyash to alkaline activator was kept constant at 2.5. After seven days of testing, the compressive strength using a 12-M NaOH solution was the highest [23]. This can be attributed to the system's increased concentration of Na ions, which were crucial for the geopolymerization process because they balanced charges and created the alumino-silicate networks that served as the mixture's binder [24]. The 12M NaOH solution outperformed the 18M solution in terms of compressive strength. At all test ages, the compressive strength generally rises with increasing NH concentration up to 10M but falls with subsequent concentration increases. This is linked to an increase in the molarity of NH and a decrease in Ms, H_2O/Na_2O, and H_2O/SiO_2 molar ratios [25].

The findings in Figures 16 to 18 clearly show that an increase in the alkaline solution and liquid-to-binder ratio results in an increase in compressive strength. Flyash mortar has a maximum compressive strength of 36.08 MPa, a liquid-to-binder ratio of 0.45, and an alkaline ratio of 2.5. The maximum compressive strength of GGBS mortar is 52.69 MPa when the liquid-to-binder ratio is 0.40 and the corresponding alkaline ratio is 2.0.

The current studies' strength increase results indicate a similar pattern to earlier research works carried out [20, 21, 25]. The compressive strength increased upto 14M, and beyond 14M, the value of compressive strength decreased.

4.3.2. Effect of Alkaline Activator/Binder Ratio

Figures 16 to 18 illustrate the impact of the alkaline activator-to-binder ratio on compressive strength. It demonstrates that mortar with a high ratio of activator to binder has demonstrated better values than mortar with a lower ratio.

In a study carried out, the results showed that for the constant molarity of NaOH solution, the compressive strength increases as the solution-to-flyash ratio increases. However, it was noteworthy up to a 0.40 solution-to-flyash ratio. Strength decreased beyond this ratio because, like self-compacting mortar, the mixture was exceedingly viscous and flowable [19]. The majority of the raw materials had already reacted after 14 days, and the response rate slowed down [24]. Previous studies have shown that as the LB ratio decreases, the consistency of mixtures decreases, which speeds up the alkaline activation process of AAFS [26].

4.3.3. Effect of Sodium Silicate/Sodium Hydroxide Ratio

The workability, setting time, and compressive strength of a geopolymer mortar were all enhanced by the adjustment in the AS/FA ratio. While improving workability, the increased AS/FA ratio also caused setting times to be delayed. Conversely, compressive strength increased with a decreased AS/FA ratio. This results from the alkaline Na_2SiO_3 solution's influence on the geopolymer process. The reaction is enhanced by the presence of Na_2SiO_3 solution [16]. A study conducted showed that the use of a Na_2SiO_3/NaOH ratio of 2.5 gave the highest compressive strength, whereas a ratio of 0.4 resulted in lower strength [23]. Studies using sodium silicate/sodium hydroxide (S/N) ratios of 0.5,1.0,1.5,2.0, and 2.5 revealed that as curing age increases, so does compressive and flexural strength. The maximum compressive strengths (up to 70.27 MPa) were recorded on the seventh day with a flyash/alkaline activator ratio of 2.0 and a Na_2SiO_3/NaOH ratio of 2.5 [24].

Using mixed activators (10M-NH and NS/NH=2.5), the maximum strength of the silico-manganese fume-slag activated mortar was 45 MPa, with a setting time of 60 minutes and a flow of 182 mm. The molar ratios of SiO_2/Na_2O, H_2O/Na_2O, and H_2O/SiO_2 that comprised the combined activators at NS/10M-NH=2.5 were 1.61, 17.33, and 10.77, respectively. Compressive strength was found to follow similar trends when the alkaline solution ratio increased, as reported in earlier research [25]. The compressive strength increases as the sodium silicate/sodium hydroxide ratio increases from 0.5 to 1.0 and then decreases [27]. The sodium silicate to NaOH ratio clearly affected the strength of the low concentration 5 M NaOH geopolymer mix. The effects were not significant for blends of 10 M and 15 M NaOH at high concentrations. While the strengths of 10 M and 15 M NaOH geopolymers were significantly greater at about 60 MPa, the strengths of 5 M NaOH geopolymers with low alkaline ratios of 0.5 and 1.0 were only 12.0 and 21.0 MPa. The strengths of 5 M NaOH geopolymer mortars were significantly superior for high alkaline ratios of 1.5 and 2.0, coming in at slightly less than 50.0 MPa as opposed to 55.0 to 65.0 MPa for 10 M and 15 M NaOH geopolymer mortar [28].

The geopolymers produced with flyash/alkaline activator ratios in the range of 1.4 to 2.3 showed high compressive strengths, ranging from 42 to 52 MPa. The optimum Na_2SiO_3/NaOH ratio was 1.5, which gives high compressive strength [29]. The mixtures of Alkali-Activated Flyash Slag (AAFS) concrete with slag content of 20 to 30%, LB ratio of 0.40, 10 M of SH, and SS/SH ratio of 1.5 to 2.5 considering the performance criteria of workability, setting time and compressive strength was optimal mixture [30]. In a study conducted, the optimum Na_2SiO_3/NaOH ratio was in the range of 0.67 to 1.00 for maximum compressive strength, which is quite different from the previous studies, which reported the optimum ratio as 2.0. This might be due to the variation in the ratio of Na_2SiO_3/NaOH, which affects the pH conditions and thus would have an effect on the gain of the strength of the geopolymer [31]. A study conducted showed that compressive strength increases with a rise in the NS/NH ratio of up to 2.5 at all test ages [32]. The results of the present study showed that the compressive strength increases with an increase in the alkaline solution ratio from 1.5 to 2.0. The trend of strength gain with the NS/NH is steady, as shown by previous studies on alkali-activated materials, which recommended an optimum ratio of NS to NH between 2-3 [33, 34].

5. Conclusion

Based on the above experimental study, the following observations are drawn. In this study, 288 specimens with 48 different mixtures are prepared to study the influence of liquid-to-binder ratio, the influence of alkaline liquid ratio and NaOH molarity on the compressive strength of flyash and GGBS geopolymer mortar.

- The workability of geopolymer mortar with flyash and GGBS mortar decreased with the increase in molarity of SH, as well as the decrease in LB ratio. The influence of GGBS on molarity and LB ratio is significant compared to the flyash mortar. The GGBS has shown lower workability values in comparison with the flyash geopolymer mortar.
- The setting time of flyash geopolymer mortar and GGBS geopolymer mortar decreases with an increase in the alkaline solution ratio.
- As the LB ratio increases from 0.35 to 0.45, the compressive strength of the mixes increases. The compressive strength increases with an increase in alkaline solution ratio upto 2.0, and beyond 2.0, the strength decreases. Hence, the optimum value of the AL ratio is 2.0.
- It is also seen that an increase of NaOH molarity upto 14M results in higher compressive strength values, and for higher NaOH molarities, the compressive strength decreases. This trend is generally observed for the mixes with LB ratios of 0.40 and 0.45 and varying alkaline solution ratios of 1.5,2.0 and 2.5.
- The GGBS mortar specimens exhibited higher compressive strength values than the corresponding flyash mortar specimens. The maximum compressive strength obtained for flyash mortar specimens and GGBS mortar specimens corresponds to a liquid binder ratio of 0.45 and an alkaline liquid ratio of 2.0.
- The specimens with 14M, LB ratio of 0.45 and AL ratio of 2.0 yielded maximum strength and is the optimum mix.

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